NASA-CR-196827

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Laboratory Astrophysics under

the Ultraviolet, Visible, and Gravitational Astrophysics Research Program

1994 Annual Technical Report for Grant NAGW-3840

Oscillator Strengths for Ultraviolet Atomic Transitions

(NASA-CR-196827) OSCILLATOR STRENGTHS FOR ULTRAVIOLET ATOMIC TRANSITIONS Annual Technical Report, 1994 (Toledo Univ.) 6 p

N95-70196

Unclas

Z9/89 0022669

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I. Introduction

The conditions within astrophysical environments can be derived from observational data on atomic and molecular lines. For instance, the density and temperature of the gas are obtained from relative populations among energy levels. Information on populations comes about only when the correspondence between line strength and abundance is well determined. The conversion from line strength to abundance involves knowledge of meanlives and oscillator strengths. For many ultraviolet atomic transitions, unfortunately, the necessary data are either relatively imprecise or not available.

Our program addresses this need for better oscillator strengths. Using beam-foil spectroscopy, meanlives and branching ratios of ultraviolet atomic transitions are studied. An ion beam of the desired element is accelerated and passes through a thin carbon foil, where neutralization, ionization, and excitation take place. The decay of an excited state is measured as a function of position, yielding the meanlife. The oscillator strength can be obtained from the meanlife and branching ratios. In addition, high-quality spectra from the Hubble Space Telescope yielded precise estimates of relative oscillator strengths for intersystem bands of CO and for dipole-allowed transitions in C_2.

II. Highlights

i) S I

In our final report for NAGW-2457, we described our results for the multiplets at 1299 and 1814 Å. In brief, our multiplet f-values for λλ 1299, 1814 of 0.121 ± 0.005 and 0.088 ± 0.005, respectively, agree reasonably well with previous experimental determinations, but are of higher precision. Our measured multiplet f-values are in general agreement with the large-scale calculations of Ho and Henry (1985) and Mendoza and Zeippen (1988). Our line oscillator strengths for λλ 1295.7, 1296.2, and 1807.3 -- prominent interstellar lines -- are somewhat lower than those suggested by Morton (1991). Moreover, since our multiplet results for λ 1814 agree with recent calculations, the discrepancy found by Roettger et al. (1989) in the ratio for λλ 1474, 1814 must lie in the multiplet at 1479 Å. This research recently appeared in print in the Astrophysical Journal (Beideck et al. 1994).

ii) S II

We have undertaken a detailed experimental study of S II oscillator strengths needed to interpret stellar spectra and obtain information concerning the interstellar medium. We have carefully measured f-values for the transitions $3p^3\ ^4S^o_{3/2}$ - $3p^24s\ ^4P_{5/2,3/2,1/2}$ at 906.85, 910.48 and 912.74 Å respectively. Preliminary results are f(907)=0.190, f(910)=0.135 and f(912)=0.065, from which a multiplet f-value of $f_{mult}(909)=0.39\pm0.02$ is obtained. This very nicely confirms the accuracy of the theoretical calculations for this transition of both Ojha and Hibbert (f=0.42) (1989) and Ho and Henry (f=0.38) (1987). Since the relatively large oscillator strengths makes these transitions usable for studying interstellar sulfur only along dilute lines of sight, we are also attempting to determine a reliable f-value for the much weaker intercombination line $3p^3\ ^4S^o_{3/2}$ - $3p^23d\ ^2P_{3/2}$ at 946.98 Å. We have detected a weak feature at this wavelength and have measured the ratio of its intensity to that of the allowed doublet transitions from the same excited level to the $2p^3\ ^2D$ levels at 1101.98 and 1102.36 Å. If one assumes that the calculated f-value of Ojha and Hibbert is also correct for this multiplet, what is needed to convert the intensity ratio to the desired f-value is a measurement of the relative efficiency of the detection apparatus employed. Such a calibration is at present being carried out and will be described below. In fact, theoretical f-values for the multiplet at 1102Å are not expected to be particularly accurate (see Ojha and Hibbert 1989), and it will be necessary to experimentally determine this value as well.

iii) Si II

The situation in Si II, where there are significant discrepancies between experimentally measured f-values and theoretical computations, was summarized in our proposal. We have begun a beam-foil spectroscopic study of these f-values, as we proposed. Early measurements are in the preliminary stage, but are quite encouraging. Since accurate f-values are now available for the lines at 1808 and 2335 Å (Bergeson and Lawler 1993; Calamai et al. 1993; Cardelli et al. 1994), the resonance lines proposed for study by us take on added importance for studies of quasar absorption-line systems.

iv) Detection Efficiency Calibration

As indicated above, we are carrying out a calibration of the relative efficiency of our detection apparatus (monochromator and photodetector efficiency) in the required range of 900-1250 Å. The calibration is being implemented using measured branching ratios (see, e.g., Klose et al. (1993) and references contained therein) in combination with a NIST argon mini-arc vacuum ultraviolet calibration source purchased with funds provided by this grant. The efficiency at a wavelength below 1140 Å is related to that at a higher wavelength by measuring the observed intensity ratio of two transitions whose branching ratio is known. The process is repeated for a number of such pairs, and the results are placed on a common footing by using the argon mini-arc to map out the efficiency in the over-1140 Å wavelength region.

v) CO and C_2

Molecules can be used as diagnostics for physical conditions in denser interstellar environments, but their usefulness depends on the quality of the molecular constants available for such analyses. In order to extract accurate abundances for these analyses, precise oscillator strengths are required. The unprecedented quality of ultraviolet data acquired with the Goddard High Resolution Spectrograph on the Hubble Space Telescope reveals the need to reexamine the available laboratory and theoretical determinations for f-values of many molecular transitions.

Two cases involve weak intersystem (triplet-singlet) transitions in CO and allowed transitions in C_2. Our detections of 7 intersystem bands (3 a′ - X, 2 d - X, and 2 e - X bands) toward zeta Ophiuchi (Federman et al. 1994) are not consistent with the available information (Morton and Noreau 1994) on the d - X and e - X bands. A combination of uncertainties in column density, equivalent width, and spectroscopic analysis is the likely cause for the discrepancy (Federman et al. 1994). For C_2, Lambert et al. (1995) obtained high-resolution data on the D - X (0-0) band (2313 Å) and moderate-resolution data on the F - X (0-0) band at 1342 Å. In examining the relative strengths of these 2 bands and the strengths of the near infrared A - X bands to that for the D - X transition, Lambert et al. (1995) noted that the astrononical results are much more consistent with available theoretical f-values than with various experimental determinations. We append abstracts of the work on CO and C_2 which will appear in the Astrophysical Journal.

vi) Student Participation

This past summer, two students received training in experimental research by participating in these measurements. The University of Toledo has been involved in the NSF Research Experience for Undergraduates program, and an outstanding senior physics major from Xavier University collaborated in this work. In addition, a first year graduate student was employed as a Summer Research Assistant and made significant contributions to the program. Both students took part in data acquisiton with the beam-foil facility and were principally resposible for making the argon mini-arc operational after its receipt from NIST in June 1994.

vii) Workshops

SRF recently participated in two workshops devoted to the exchange of ideas between astrophysicists and spectroscopists. The first one, which was organized by the Ultraviolet, Visible, and Gravitional Astrophysics Research Program at NASA, took place in Pasadena, California during February. Here, SRF focussed on the needs that arose from our laboratory work on atoms. In particular, he noted that additional classical spectroscopic research on energy levels in complex atoms (e.g., chlorine and elements heavier than zinc) is needed and that the f-value for the 1479 Å multiplet in S I may need an especially careful treatment because there appears to be cancellations in the radial matrix elements as well as mixing from nearby energy levels. He helped draft the recommendations of the workshop for the personnel at NASA Headquarters. The second workshop, in August/September, had Brussels, Belgium as the venue. The recently discovered inconsistencies between astronomical, experimental, and theortical f-values for the molecules CO and C_2 were also reported here. His invited contribution to this workshop will appear as part of the proceedings in an upcoming volume of the A.S.P. Conference Series.

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Intersystem Transitions of Interstellar Carbon Monoxide Toward Zeta Ophiuchi[1]

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ABSTRACT

Absorption from seven intersystem (triplet-singlet) transitions of interstellar ^{12}CO were detected in ultraviolet spectra of ζ Oph. The observed equivalent widths are approximately consistent with the transitions' predicted f-values (Morton & Noreau 1994) and the ^{12}CO column density derived from the weakest of the observed A–X bands. These unsaturated intersystem transitions provide the opportunity to measure the ^{12}CO column density for heavily reddened (dense) sight lines. Laboratory measurements of oscillator strengths more precise than available ones will be needed to derive accurate column densities.

Subject headings: abundances - ISM:molecules - molecular data:CO - ultraviolet: spectra

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[1]Based on observations obtained with the NASA/ESA *Hubble Space Telescope* through the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NASA-26555.

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Hubble Space Telescope Observations of C_2 Molecules in Diffuse Interstellar Clouds[1]

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ABSTRACT

Interstellar C_2 F-X (1342Å) and D-X (2313Å) bands in the spectrum of ζ Oph were detected using the *Goddard High Resolution Spectrograph* on the *Hubble Space Telescope*. The total C_2 column density is $(1.79 \pm 0.06)10^{13}\,\mathrm{cm}^{-2}$ for an adopted f-value of 0.0545 for the 2313 Å band of the Mulliken (D-X) system. Relative f-values for the 0-0 F-X, 0-0 D-X, and 2-0 A-X (Phillips) bands are derived by combining ultraviolet and near-infrared spectra: $f_{00}^{\mathrm{FX}}/f_{00}^{\mathrm{DX}} = 1.83 \pm 0.18$ and $f_{20}^{\mathrm{AX}}/f_{00}^{\mathrm{DX}} = 0.0226 \pm 0.0029$. For the Mulliken system, lines are detected up to a rotational level $J'' = 24$. The relative populations along the rotational ladder are shown to be consistent with the physical and environmental conditions suggested by other diagnostics. Interstellar C_2 molecules were detected towards ξ Per ($N(C_2) = (0.80 \pm 0.23)10^{13}\,\mathrm{cm}^{-2}$) but not towards β^1, π, and ω^1 Sco ($N(C_2) \leq 0.17 \times 10^{13}\,\mathrm{cm}^{-2}$).

Subject headings: abundances - ISM: molecules - stars: individual (ζ Ophiuchi, ξ Persei, β^1, π and ω^1 Scorpii)

[1]Based on observations obtained with the NASA/ESA Hubble Space Telescope through the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA Contract NASA-26555.